



Development projects at AIP

Christoph Pfrommer¹

presents work by

T. Thomas¹, K. Ehlert¹, G. Winner¹, M. Werhahn¹, M. Pais¹,
P. Girichidis¹, T. Berlok¹, M. Sparre¹, R. Weinberger², R. Pakmor²

¹Leibniz Institute for Astrophysics Potsdam (AIP)

²Heidelberg Institute for Theoretical Studies (HITS)

AREPO Developer Workshop 2018, Heidelberg – Jun 2018

Outline

1 Cosmic ray transport

- CR streaming and diffusion
- Spectral CR transport
- AGN feedback

2 Beyond standard galaxy formation

- Intracluster medium
- Circumgalactic medium
- Conclusions



Outline

1 Cosmic ray transport

- CR streaming and diffusion
- Spectral CR transport
- AGN feedback

2 Beyond standard galaxy formation

- Intracluster medium
- Circumgalactic medium
- Conclusions



AIP

Alfvén-wave regulated CR transport (Timon Thomas)

- coupled equations for CR energy and flux density, ε_{cr} and f_{cr} and Alfvén-wave energy density $\varepsilon_{a,\pm}$ (Thomas & Pfrommer 2018):

$$\frac{\partial \varepsilon_{\text{cr}}}{\partial t} + \nabla \cdot [\mathbf{u}(\varepsilon_{\text{cr}} + P_{\text{cr}}) + \mathbf{b}f_{\text{cr}}] = \mathbf{u} \cdot \nabla P_{\text{cr}} \quad (1)$$
$$- \frac{v_a}{3\kappa_+} [f_{\text{cr}} - v_a(\varepsilon_{\text{cr}} + P_{\text{cr}})] + \frac{v_a}{3\kappa_-} [f_{\text{cr}} + v_a(\varepsilon_{\text{cr}} + P_{\text{cr}})],$$

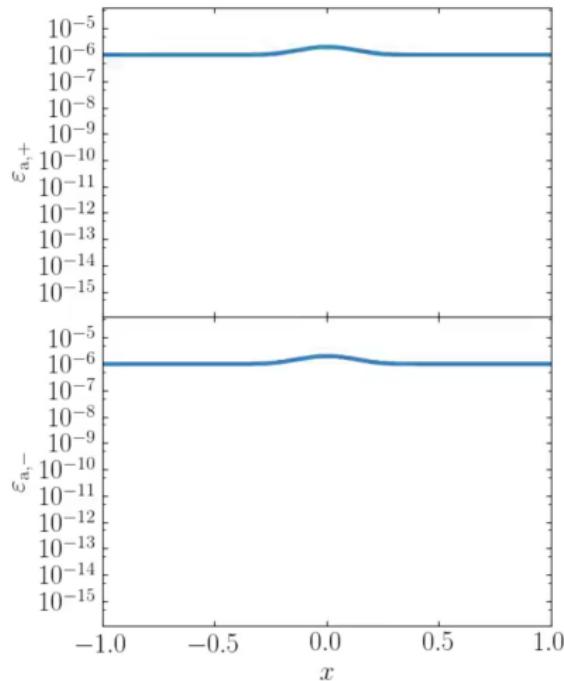
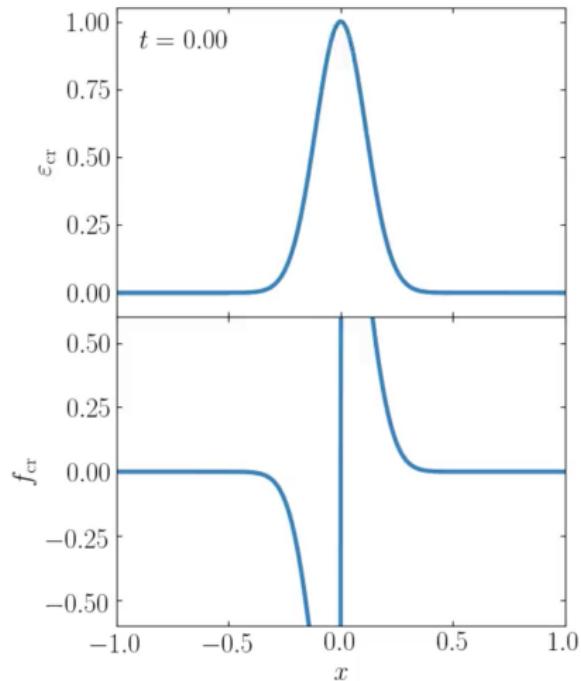
$$\frac{\partial f_{\text{cr}}}{\partial t} + \nabla \cdot (\mathbf{u}f_{\text{cr}}) + \frac{c^2}{3} \mathbf{b} \cdot \nabla \varepsilon_{\text{cr}} = -(\mathbf{b} \cdot \nabla \mathbf{u}) \cdot (\mathbf{b}f_{\text{cr}}) \quad (2)$$
$$- \frac{c^2}{3\kappa_+} [f_{\text{cr}} - v_a(\varepsilon_{\text{cr}} + P_{\text{cr}})] - \frac{c^2}{3\kappa_-} [f_{\text{cr}} + v_a(\varepsilon_{\text{cr}} + P_{\text{cr}})],$$

$$\frac{\partial \varepsilon_{a,\pm}}{\partial t} + \nabla \cdot [\mathbf{u}(\varepsilon_{a,\pm} + P_{a,\pm}) \pm v_a \mathbf{b} \varepsilon_{a,\pm}] = \mathbf{u} \cdot \nabla P_{a,\pm} \quad (3)$$
$$\pm \frac{v_a}{3\kappa_\pm} [f_{\text{cr}} \mp v_a(\varepsilon_{\text{cr}} + P_{\text{cr}})] - S_{a,\pm}.$$



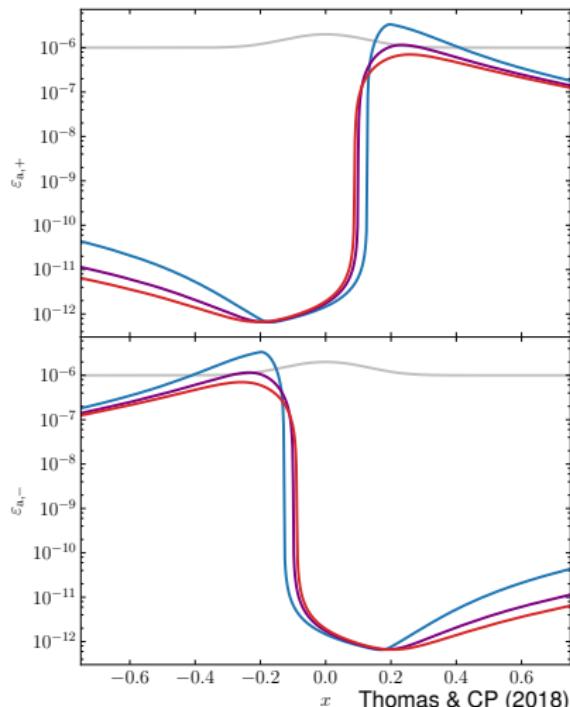
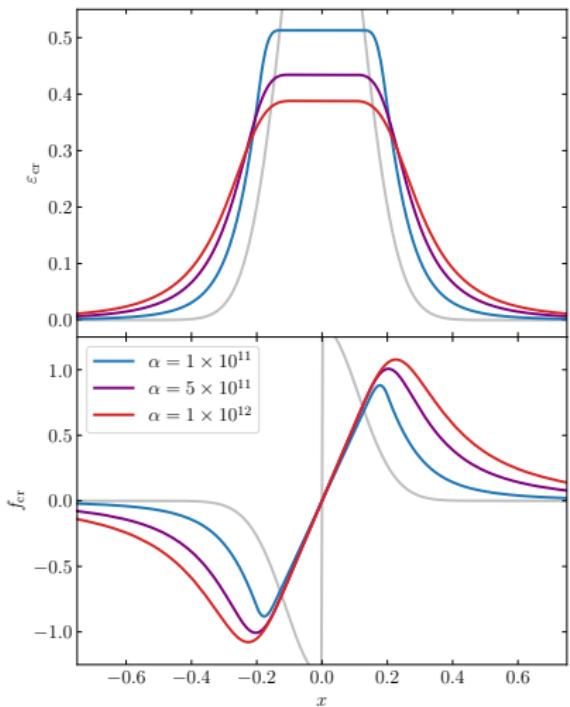
Non-equilibrium CR streaming and diffusion

Coupling the evolution of CR and Alfvén wave energy densities



Non-equilibrium CR streaming and diffusion

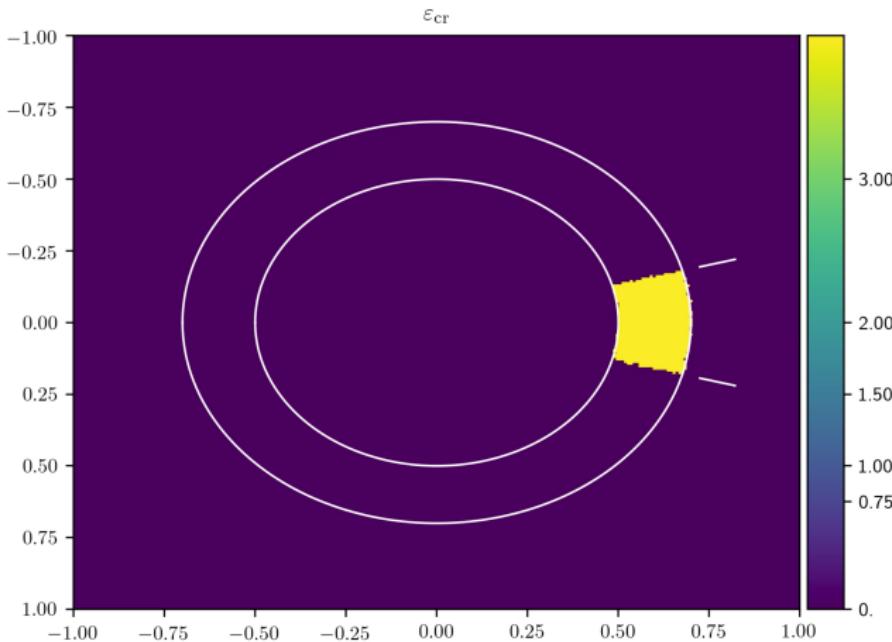
Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)



Non-equilibrium CR streaming and diffusion – AREPO

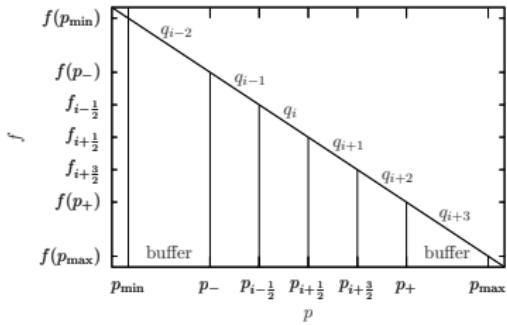


Thomas, CP & Pakmor (2018)



Spectral transport of CR ions (Philipp Girichidis)

- full spectrum in every cell
 - logarithmic bins in CR momentum
 - buffer bins at high and low end

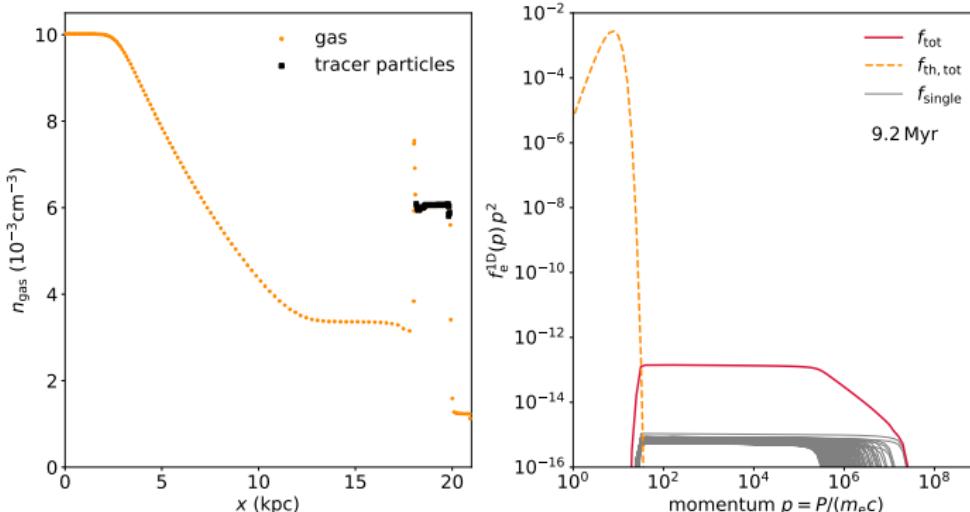


- discretise Fokker-Planck eq.
 - piecewise power-laws
 - couple n and e to hydro eq.
 - procedure operator-split
 - CR physics based on FP eq.
 - 1 Coulomb losses
 - 2 hadronic losses
 - 3 adiabatic process
 - coupling and transport (n, e)
 - 1 advection
 - 2 compression ($\nabla \cdot \mathbf{v}$)
 - 3 diffusion



Spectral transport of CR electrons (Georg Winner)

Shock tube problem with CRe shock acceleration and synchrotron/IC cooling



- $\mathcal{M} = 10$, $v_s = 1000 \text{ km s}^{-1}$
 - CRe spectrum on tracer particles, injection at shock
 - mass weighting: $w_{\text{tracer}} \propto m_{\text{tracer}} / \rho_{\text{gas}}$

Spectral CR transport



NASA/JPL-Caltech/STScI/CXC/UofA

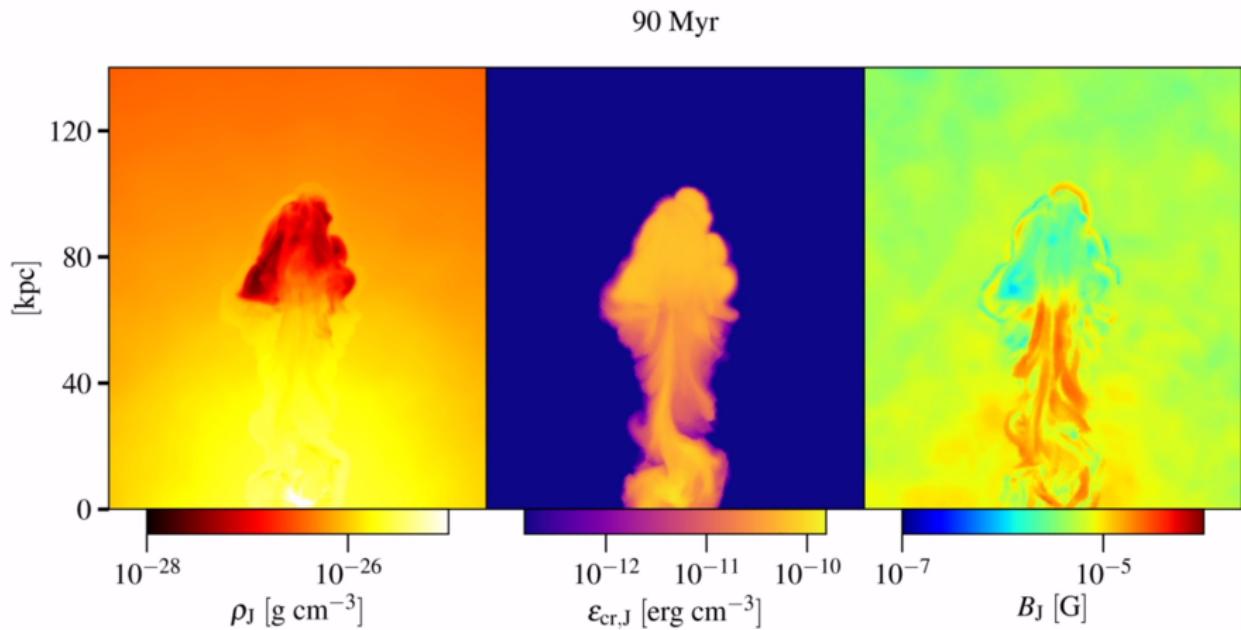
super wind in M82

- **Multi-frequency spectrum** of simulated galaxies, galaxy clusters, AGNs (Maria Werhahn):
 - hadronic CR interactions
 - secondary CR electrons
 - primary CR electrons
- **CR ionization in the ISM**
- **spectral CR dynamics** vs. steady state assumption



AIP

Jet simulation: gas density, CR energy density, B field



Ehlert, Weinberger, CP, Pakmor, Springel (2018)

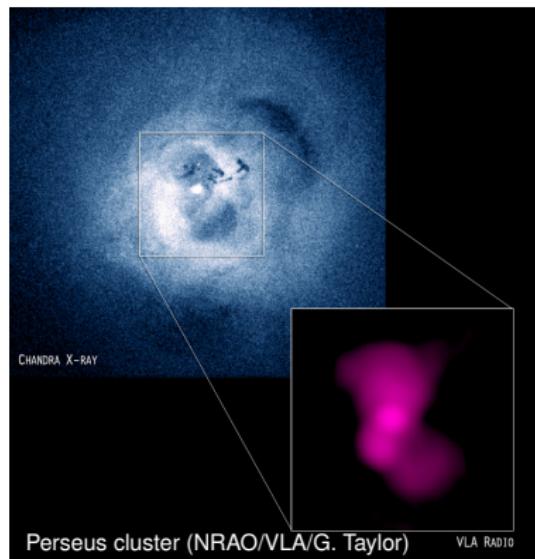


AIP

AGN feedback + CR physics: next steps

lead by **Kristian Ehlert + Rainer Weinberger:**

- improved modeling of CR transport
- self-regulated heating cooling cycle:
implementation of cold accretion
- cosmological settings
- many applications:
 - cluster cooling flow problem
 - AGN outburst from the Milky Way (Hestia project)
 - ...



Outline

1 Cosmic ray transport

- CR streaming and diffusion
- Spectral CR transport
- AGN feedback

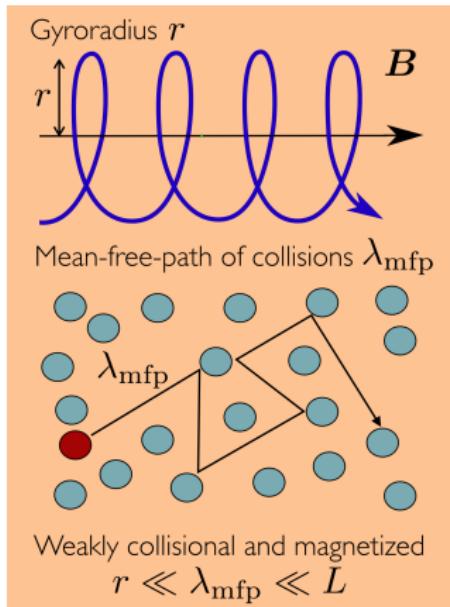
2 Beyond standard galaxy formation

- Intracluster medium
- Circumgalactic medium
- Conclusions



AIP

Physics of the intracluster medium



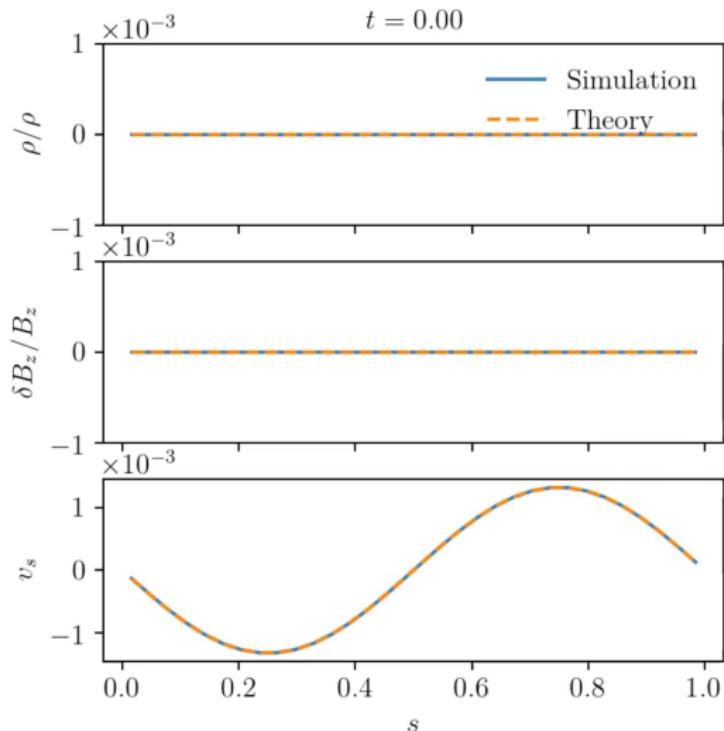
- transport of heat and momentum is along magnetic field lines
- important consequences for the intracluster medium!
- Braginskii MHD:

$$\frac{\partial \rho \mathbf{u}}{\partial t} = -\nabla \cdot \boldsymbol{\Pi}, \quad \frac{\partial \varepsilon}{\partial t} = -\nabla \cdot (\boldsymbol{\Pi} \cdot \mathbf{u}),$$

$$\boldsymbol{\Pi} = -\Delta p \left(\mathbf{b} \mathbf{b} - \frac{1}{3} \right),$$

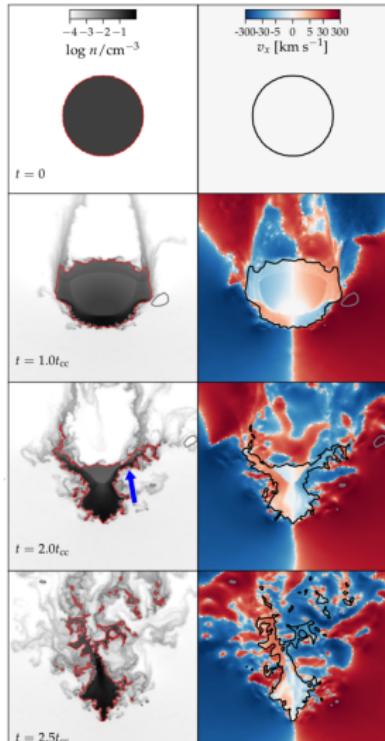
$$\Delta p = \rho \nu_{||} (3 \mathbf{b} \mathbf{b} : \nabla \mathbf{u} - \nabla \cdot \mathbf{u}),$$

Braginskii viscosity in AREPO (Thomas Berlok)



Circumgalactic medium and outflows (Martin Sparre)

Cloud-crushing simulations and thermal instability in 2D and 3D



- gas clouds fragment if their cloud sizes are much larger than their cooling length
- paper 1: cloud-crushing simulations with radiative cooling
- paper 2: cloud-crushing simulations with MHD, anisotropic conduction, self-gravity
- paper 3: cosmological simulations with a patch refined to very high resolution

Sparre, CP, Vogelsberger (2018) etc.

Development projects at AIP

● cosmic ray transport

- new CR transport scheme – *Timon Thomas*:
simulations of galaxies, clusters, AGNs, ...
- CR spectral transport of protons and electrons –
Philipp Girichidis, Georg Winner, Maria Werhahn:
simulations & multi-frequency spectra of galaxies & clusters
- AGN feedback with CR physics –
Kristian Ehlert, Rainer Weinberger@ITC



AIP

Development projects at AIP

● cosmic ray transport

- new CR transport scheme – *Timon Thomas*:
simulations of galaxies, clusters, AGNs, ...
- CR spectral transport of protons and electrons –
Philipp Girichidis, Georg Winner, Maria Werhahn:
simulations & multi-frequency spectra of galaxies & clusters
- AGN feedback with CR physics –
Kristian Ehlert, Rainer Weinberger@ITC

● beyond standard galaxy formation

- intracluster medium: Braginskii MHD – *Thomas Berlok*
- circumgalactic medium: cloud shattering – *Martin Sparre*

